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University of Zimbabwe

Body fluid shifts in soldiers after a jogging/walking exercise in the heat: effects of water and electrolyte solution on rehydration

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Abstract

Objectives: To examine the relationships between dehydration and body fluid shifts and the effects of ingesting water or oral rehydration solution or no fluid during and after exercise in the heat [mean (SE)] temperature, 40.5 (0.66)°C and 32 (3.7)% humidity.

Design: PRE and POST three hours exercise comparative study.

Setting: Zimbabwe National Army Wafa-Wafa Training Camp, Kariba, Zimbabwe.

Subjects: 18 male soldiers volunteered to be studied during and after a 20 km (three hour) jogging/walking exercise in full kit.

Main Outcome Measures: Body mass, total body water, extracellular water, intracellular water, plasma osmolality, plasma sodium, and volume changes compared using paired t-test.

Results: Total body water decreased by 4.9 (0.38) l ($p < 0.02$) in soldiers exercising without fluid, 1.5 (0.3) l (oral rehydration solution), 2.4 (0.8) l (water). Extracellular water decreased by 3.6 (0.3) l ($p < 0.05$), 1.3 (0.2) l, 1.7 (0.3) l, and intracellular water decreased by 1.3 (0.1) l, 0.2 (0.01) l, 0.7 (0.01) l respectively in these

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groups. Plasma volume decreased by [mean (SE)] 16 (1.4)% on no fluid, three (0.3)% on oral rehydration solution, five (0.3)% on water. Plasma osmolality increased significantly from 285 (1.0) to 301 (2.3) mosmol.kg⁻¹ ($p < 0.001$) in subjects exercising without fluid and from 283 (2.0) to 291 (0.7) mosmol.kg⁻¹ ($p < 0.02$) in subjects taking oral rehydration solution. No significant increases were observed when taking water only.

Conclusions: During dehydration, total body water loss was derived from both fluid compartments but extracellular water contributed the most. Effective rehydration depends on adequate replacement of electrolytes lost from each fluid compartment. Water alone may not provide adequate rehydration.

Introduction

Intense physical activity in hot conditions is limited by the distribution of body water and the ability to maintain blood volume. Effective rehydration therapy is limited by our knowledge of what actually happens in practice and the efficacy of recommended treatments in the field.

Prolonged exercise in hot environments without adequate fluid replacement leads to dehydration due to excessive sweating¹ and results in a decrease in plasma volume² and an increase in plasma osmolality.³ Dehydration is known to limit the capacity to perform physical work and to jeopardize the health of athletes.⁴⁻⁶ Sawka and Pandolf⁶ have suggested that the fluid in sweat initially comes from the extracellular fluid space but as dehydration intensifies, the increase in extracellular fluid osmolality causes water to flow from the intracellular fluid compartment. However, observations on extracellular space and intracellular space adjustments during severe dehydration remain inconsistent and diverse.⁷⁻⁹

Observations from previous studies^{3,10,11} have suggested that post exercise rehydration can be effective and complete if fluids containing electrolytes in particular sodium are ingested. We have measured the effects of ingesting water alone or electrolyte solution on rehydration. We suggested that the electrolytes (sodium and potassium) of oral rehydration solution would enhance fluid replenishment in the body fluid compartments compared to water. However, the question remains of determining how water loss is partitioned between the extracellular fluid space and the intracellular fluid compartment.¹² We have examined the relationships between dehydration and body fluid shifts during exercise in extreme heat and we suggest that exercise-induced dehydration would lead to greater fluid loss from the extracellular fluid space than by the intracellular fluid space.

Materials and methods

Subjects.

Eighteen male Zimbabwe National Army soldiers [mean (SE)] age, 24 (1.0) years, height, 176 (2.0) cm, and body mass, 75 (2.0) kg volunteered to participate in the study. The soldiers went through three hours (20 km) of jogging/walking exercise (alternating 15 minutes jogging with five minutes walking). If the subjects could not cover the 20 km in three hours, exercise was terminated at three hours or by exhaustion. They gave their informed consent after being

briefed of the dangers and benefits of the project. Measurements were done in three exercise conditions. One group ($n=6$) exercised with no fluid and took water *ad libitum* in the post exercise period (no fluid). A second group ($n=6$) had access to oral rehydration solution (ORS: DatLabs, Harare, Zimbabwe) containing sodium 67 mmol.l⁻¹, potassium 15 mmol.l⁻¹, chloride 60 mmol.l⁻¹, bicarbonate 22 mmol.l⁻¹, dextrose 7.5 g.100 ml⁻¹. The third group ($n=6$) had access to water throughout. The dress for the study was light uniforms with boots but no weapons or extra load was carried. The protocol was approved by the Zimbabwe Defence Forces Health Services Ethics Committee, the Zimbabwe Medical Research Council and the Drug Control Council.

Experiment Design.

Two weeks before training started, extracellular water was evaluated using analysis of the bromide space in all participants. The subjects reported to the laboratory with urine samples (for deuterium oxide analysis), normally hydrated but without breakfast. The subjects had their nude body mass taken and redressed. A venous blood sample was taken by venepuncture and immediately after this, the subjects took one ml / kg body mass or two gms (19.4 mmol) sodium bromide (99.99 + %) (Aldrich Chemical Company, Dorset, England) and 15 gms deuterium oxide (²H₂O, 99.9 atom % D), (Sigma Chemical Co. St. Louis, MO. USA) plus 50 ml tap water used for rinsing the sample container. A blood sample for bromide analysis was taken three hours (post dose) and urine samples for deuterium oxide determination were collected at one, two, three, four, five hours.

At 09.30 hours on the morning of the exercise, the subjects reported to the laboratory. They were seated for 30 minutes before a blood sample was obtained by venepuncture; blood was taken without stasis. A urine sample was then collected and they had their nude body mass measured and then subjects dressed in camouflage, boots and combat caps. At 11.30 hours they assembled and took sodium bromide and deuterium oxide as above and the three hour run started immediately. No food was taken during the three hours exercise period. Urine samples were collected in small plastic containers at one, two, three, four and five hours and kept on dry ice and later at -20°C.

Immediately after the run (three hours) a cannula was inserted into a superficial forearm vein (it remained in place until the last sample was collected) and a blood sample for bromide measurement taken. The cannula was kept patent by flushing periodically with sterile saline.

They were weighed and rested in a sitting position for 30 minutes and another blood sample for plasma electrolytes was taken. Immediately after this they took 10 ml/kg body weight of water (no fluid and water trials) or oral rehydration solution (760 (36) ml, 740 (41) ml, 780 (28) ml) respectively for these groups. After this they continued to take fluids *ad libitum*. Further blood samples were collected one hour and two hours after drinking started. No food or drink, other than the test drink was allowed until after this sample had been collected. To assess the effect of rehydration on total body water recovery, the subjects took another deuterium dose two hours after exercise and urine samples were collected at one hour intervals for five hours. After collecting the last urine sample body mass was measured i.e. seven hours after drinking started.

Analytical Procedures.

Immediately upon collection, one aliquot of blood was added to heparin tubes, centrifuged and part of the plasma was stored on dry ice for subsequent measurement of plasma sodium by flame photometry and plasma osmolality by freezing point depression. The other part of the plasma was stored at -20°C for later analysis of bromide. Another aliquot of blood was added to EDTA tubes (1.5 mg.ml⁻¹) for measurement of haematocrit by microcentrifugation and haemoglobin by cyanmethemoglobin technique. Percent changes in plasma volume were calculated from haematocrit and haemoglobin according to Dill and Costill.¹³

All frozen urine and blood samples were analyzed at the Department of Physiology, Dundee University (Scotland) by isotope ratio mass spectrometry (deuterium oxide) and spectrophotometry (sodium bromide). Deuterium oxide was measured and calculated according to Scrimgeour *et al.* and Bell¹⁵ and a spectrophotometer (LKB Ultrospec II, Biochrom, Cambridge, England) was used to read off the result at 520 nm. Intracellular water (ICW) was calculated as the difference between total body water (TBW) and extracellular water (ECW): ICW = TBW-ECW.

Percent plasma volume was calculated according to Dill and Costill.¹³

Statistical Procedures.

All data was subjected to a two way repeated measures analysis of variance and where appropriate, Duncan's multiple range test was used. Pre and post exercise values were compared using the paired t-test. Linear regression was used to determine correlations of changes in extracellular water to changes in total body water and plasma osmolality. Values are reported as mean (SE). P values of less than 0.05 were considered statistically significant.

Results

The results of body mass, total body water, extracellular water and intracellular water are presented in Table I.

Body Mass.

Table I : Body mass, total body water (TBW), extracellular water (ECW) and intracellular water (ICW) before and after three hour exercise and seven hour post exercise rehydration. Subjects ingested water or oral rehydration solution (ORS) or no fluid during exercise. The no fluid group took water after exercise. Values are mean (SE): significantly lower **p*<0.05; ***p*<0.02 compared to pre-exercise.

Variables	No Fluid	ORS	Water
Body mass, kg			
Before	75.8 (2.0)	75.4 (3.0)	74.8 (2.0)
After	70.8 (3.0)**	73.6 (2.6)	72.1 (1.8)
Rehydration (7 h)	72.6 (1.8)	76.5 (4.6)	74.0 (3.4)
TBW (L)			
Before	44.2 (3.0)	44.1 (3.2)	44.4 (3.2)
After	39.3 (3.6)	42.6 (3.00)	44.4 (3.2)
Rehydration (7 h)	41.8 (3)	45.0 (2.0)	43.7 (2)
ECW (L)			
Before	14.4 (1.0)	14.6 (1)	15.3 (1.2)
After	10.8 (1.0)	13.2 (0.6)	13.6 (1.1)
ICW (L)			
Before	29.8 (2.0)	29.5 (1)	29.1 (2.2)
After	28.5 (1.3)	29.3 (2.4)	28.4 (1.8)

Body mass fell by five (0.4) kg (*p*<0.02) for the no fluid test; by 1.8 (0.1) kg when taking oral rehydration solution and by 2.7 (0.5) kg in the water test (*p*>0.05). Seven hours after rehydration, subjects in the oral rehydration solution test recovered body mass to above pre-exercise body mass, but those drinking water remained below the pre-exercise body mass.

Total Body Water.

Total body water decreased by 7%, 2% and 3% of body mass respectively for these groups. Two subjects exercising with no fluid lost 6.2 and 6.1 l (9% of body mass) and they failed to cover the 20 km in three hours, exercise was terminated due to fatigue.

Extracellular Water.

Extracellular water loss was 25%, 9.6% and 11% of pre-exercise extracellular water respectively for these groups (Figure I). Significant positive correlations were found between changes in extracellular water and changes in total body water (*p*<0.01) (Figure II); between changes in extracellular water and changes in plasma osmolality (*p*<0.01).

Intracellular Water.

Intracellular water also decreased by 4.4%, 0.7% and 2.4% of pre-exercise intracellular water respectively for these groups.

Plasma Osmolality.

Plasma osmolality rose by 16 mosmol.kg⁻¹, by eight mosmol.kg⁻¹ and by two mosmol.kg⁻¹ respectively. Ingesting fluids after exercise caused plasma osmolality to fall to 28 (0.9) mosmol.kg⁻¹, to 288 (1.1) mosmol.kg⁻¹ and to 282 (0.7) mosmol.kg⁻¹ respectively. In the oral rehydration solution test, plasma osmolality remained above pre-exercise concentration throughout the rehydration period.

Figure I: Extracellular water after three hours exercise. Significantly lower than pre-exercise zero hours $**p < 0.05$.

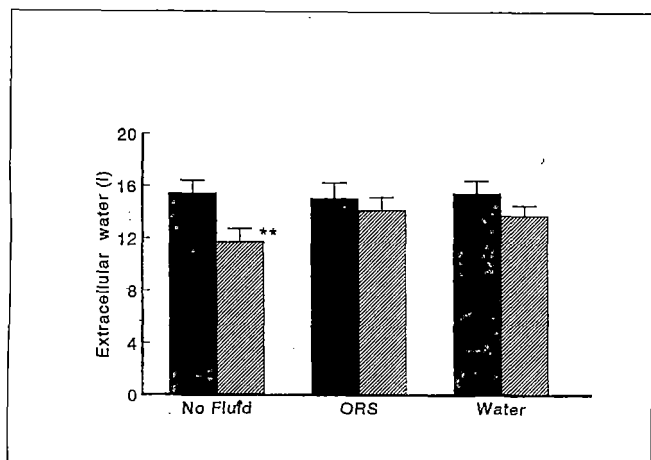


Figure II: Correction of percent change in extracellular water to percent change in total body water. Changes in extracellular water was positively correlated $r = 0.98$ ($p < 0.001$) to changes in total body water.

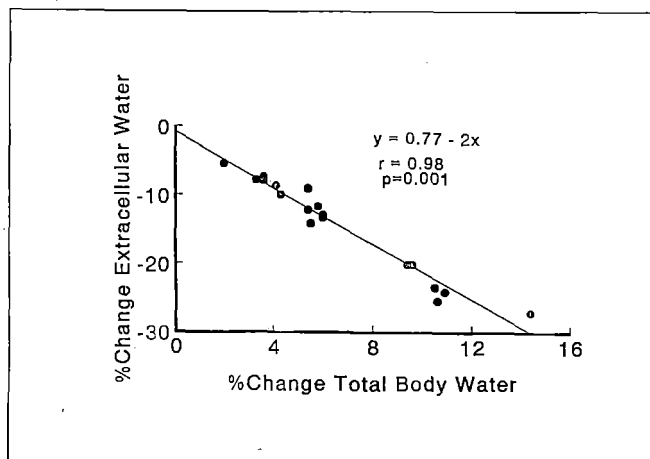
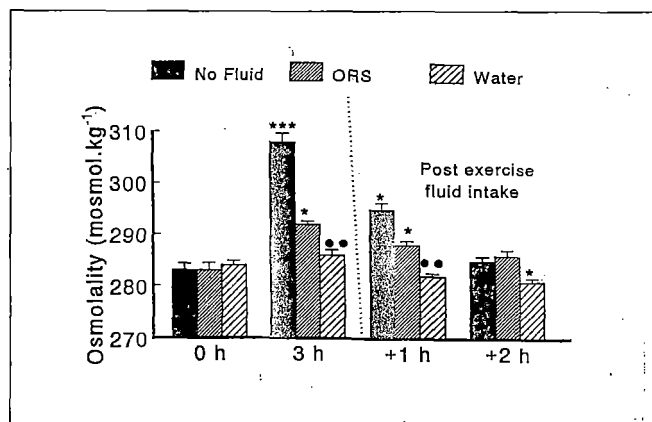


Figure III: Plasma osmolality before exercise, during exercise with no fluid, exercise with intake of water or oral rehydration solution and during post exercise rehydration two hours. Significantly higher than pre exercise $**p < 0.001$; lower than no fluid $**p < 0.05$; lower than ORS $**p < 0.05$.



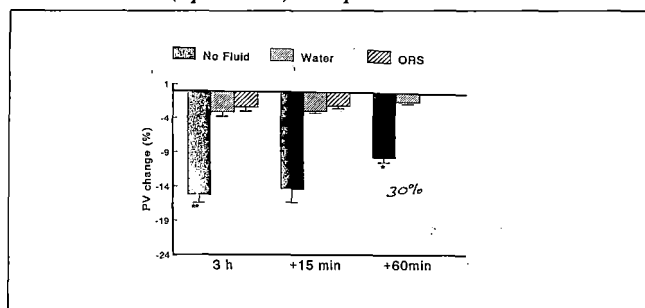
Plasma Sodium.

Plasma sodium concentration rose by 8% ($p < 0.01$), by 2.1% and decreased by 1.4% respectively for these groups. After exercise, plasma sodium concentration was maintained above pre-exercise concentration (144 (2.2) mmol.l^{-1}) when subjects took oral rehydration solution. Drinking water caused plasma sodium to fall further to 140 (0.4) mmol.l^{-1} . Positive correlations were found between percent changes in plasma sodium and percent changes in body mass ($p < 0.05$).

Percent Changes in Plasma Volume.

Plasma volume fell ($p < 0.001$) when exercising with no fluid but the fall in subjects taking either oral rehydration solution or water was minimized. After exercise, oral rehydration solution restored plasma volume to 1.6 (0.5)% compared to 0.5 (0.01)% for the water test and to -6.7 (1.1)%, this was ($p < 0.05$) compared to three hours for the no fluid group taking water after exercise.

Figure IV: Plasma volume (%) change when taking no fluid, when taking water or oral rehydration solution and after 60 minutes rehydration; significantly lower compared to taking water or ORS; after 60 minutes rehydration it remains lower ($*p < 0.05$) compared to ORS.



Fluid Intake.

The oral rehydration solution test drank more fluid compared to those taking water; subjects in the oral rehydration solution test ingested $2\,480$ (49) ml during exercise and $4\,670$ (66) ml after exercise; $2\,100$ (42) ml before and $3\,450$ (46) ml after exercise for the water test. The no fluid group ingested $3\,790$ (37) ml of water after exercise.

Discussion

This study has provided an analysis of fluid volume redistribution during exercise-induced dehydration in soldiers doing field exercise in a hot and dry environment. Our data indicate that in all the exercise conditions observed during the present study, the extracellular space contributed more than the intracellular space to total body water loss. Thus, it appears that the level and intensity of dehydration determines the degree to which the intracellular water contributes to the fluid deficit^{7,16} and Sawka and Pandolf⁶ have shown that during moderate dehydration, water deficit initially comes from the extracellular compartment. As dehydration increases, intracellular fluid will also contribute to the water deficit.^{12,16}

It has been suggested that even during intense dehydration, further plasma volume decline is prevented not only by contributions from intracellular and interstitial water to maintain blood volume,³ but also from water released from the breakdown of glycogen.⁶ The rise in plasma osmolality and sodium, the fall in plasma volume and the positive relationship between changes in extracellular water and changes in total body water ($r=0.978$); and plasma osmolality ($r=0.936$); and between changes in plasma sodium and body mass loss ($r=0.641$) in subjects exercising, without fluid, add to the suggestion that the extracellular volume was significantly decreased. Therefore, our observations support those of Robinson¹⁷ who studied two groups of subjects. One group had a total sodium chloride intake of 140 meq Na^+ per day and one litre of low Na^+ tap water and the other group had this basic Na^+ and water intake, plus replacement of all sweat Na^+ and water lost during heat exposure.

Robinson¹⁷ found that the weights of the subjects correlated well with the state of Na^+ balance, indicating that the weight changes were mainly due to changes in extracellular volume.

In contrast to our observation, Kozlowski and Saltin⁹ and Åstrand and Saltin¹⁸ found small decreases in extracellular fluid after exercise dehydration. Kozlowski and Saltin⁹ attributed this lesser decrease in extracellular water to the water of combustion i.e. from fat and carbohydrate and water stored with glycogen which amounts to approximately 1.1 litres.

The continued loss of water from the extracellular water volume leads to a rising sodium concentration, a rising osmolality and a fall in its volume and this establishes an osmotic gradient with the intracellular water.¹⁹ In the present study, the increases in plasma osmolality and sodium observed in subjects exercising with no fluid reflects a high loss of hypotonic fluid from the plasma due to excessive sweating.^{9,20,21}

In subjects taking either oral rehydration solution or water, the fall in extracellular fluid space was minimized and no significant fluid losses were observed in the intracellular compartment suggesting that fluid shift from the intra- to the extracellular fluid compartment was probably at a steady state.⁷ Our data are consistent with those of Durkort *et al.*⁷ who studied rats dehydrated by passive heating and observed that the intracellular fluid is unaltered during moderate dehydration but as the level of body water loss increases, intracellular fluid will also become reduced.

Another observation of the present study is that despite the falls in plasma osmolality and sodium with intake of water, plasma volume recovered the least thus, the drive to drink was probably maintained by the decreased plasma volume.³ Because the water test ingested less fluid compared to the oral rehydration solution test, the results suggest that plasma osmolality and sodium are probably more important than plasma volume in influencing drinking behaviour.

The ability to produce effective post exercise rehydration will depend on effective provision and ingestion of fluids

containing electrolytes (especially sodium and potassium) which are likely to replace deficits from the extracellular and intracellular fluid compartments respectively.^{3, 10, 11} In the present study, subjects ingesting oral rehydration solution maintained plasma osmolality and sodium above pre-exercise concentration thereby maintaining the drive to drink more fluids³ and restored body water, body mass and plasma volume within the seven hours rehydration period. Ingesting oral rehydration solution (containing sodium (67 mmol.l^{-1}) and potassium (15 mmol.l^{-1}) and maintenance of plasma osmolality and sodium in these subjects probably facilitated the early phase of rehydration during which water and electrolytes move dynamically among fluid compartments to attain new steady states thereby influencing drinking behaviour.³ In the water test, both plasma osmolality and sodium decreased below pre-exercise concentration, less fluid was ingested and body mass and body water were not recovered at the end of the rehydration period. Costill and Sparks²¹ observed increased serum electrolytes following a 4% dehydration and when they used demineralized water to replace sweat losses during rehydration, serum sodium and chloride concentrations fell two to 4% below normal. Maughan *et al.*¹⁰ have also shown that ingestion of plain water stimulates urine output and this effect will delay rehydration.

As previously described by Pandolf *et al.*¹² the ability to perform exercise in hot environments depends on the distribution of body water and the ability to maintain blood volume. Our data indicate that during dehydration, body water deficit was derived from both the extracellular and intracellular compartments, but extracellular water volume was the major contributor of the water deficit. Ingesting fluid during exercise minimized fluid requirements after exercise and effective rehydration was better achieved by ingesting oral rehydration solution. Water alone may not provide adequate rehydration.

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